# Two-Dimensional Hydraulic Modeling Approach to Linking Stream Morphology and Aquatic Habitat Quality

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**Abstract:** A two-dimensional hydrodynamic model (River2D) was utilized to evaluate the relationship between geomorphic condition (as estimated using an existing rapid assessment protocol) and instream habitat quality in small Vermont streams. Six stream reaches ranging in geomorphic condition from good to poor according to the protocols were utilized for this study. We conducted detailed topographic surveys, quantified bed substrate, and measured velocity values during baseflow conditions. The reach models were calibrated with realistic roughness values based on field observations and pebble counts. After calibration, the flows were scaled up to median and bankfull flows for additional analysis. The weighted usable area (WUA) of habitat was calculated for each stream, at both median and bankfull flow, using the modeled parameters and habitat suitability curves for brown trout (*Salmo trutta*). Habitat for this fish was predicted using habitat parameters of velocity, depth, and channel substrate type suitabilities for adult, juvenile, and fry stages. The predictions of WUA, show a negative correlation to the stream geomorphic score, indicating that the often-used rapid protocols, do not directly relate to instream habitat conditions. Future research will include evaluating WUA at sub-reach scales, simulating additional flow conditions, expanding these WUA predictions to other species, computing additional habitat indices, and comparing modeled habitat parameters with actual biological data collected from these streams.

***Keywords***: hydraulic modeling; aquatic habitat; WUA; brown trout; stream morphology

## 1. INTRODUCTION

Geomorphic assessment protocols based on Rosgen [1996] have become particularly common and are being used to categorize river and stream reaches as stable or unstable, as well as to predict rates of streambank erosion [Prajapati and Lavania, 1988; Harmel and Dutnell, 1998]. In Vermont, the Agency of Natural Resources (VTANR) utilizes fluvial morphology and channel stability assessments as a foundation for all of its watershed protection, management and restoration activities [VTANR, 2004]. Since aquatic biota is intimately linked to their physical environment, stream geomorphic condition potentially has important implications for ecosystem integrity [Sullivan et al., 2004]. Many government agencies utilizing rapid geomorphic assessments assume that having high-quality morphologic or stable physical conditions directly translates to improved aquatic habitat and biodiversity. This connection between geomorphic condition and actual aquatic habitat and stream health has not been proven.

Hydraulic models are useful tools for assessing the quality and quantity of aquatic habitat [Milhous, 1999; Crowder and Diplas, 2002]. A typical example of this approach is the one-dimensional Physical Habitat Simulation model (PHABSIM), which is used to predict micro-habitat conditions (in terms of depth, velocities, and channel indices) and the relative suitability of those conditions to aquatic life [Bovee 1982; Milhous et al., 1989; Gordon et al., 1992; Milhous, 1999]. The PHABSIM methodology quantifies the physical habitat available within a stream according to target species habitat suitability index (HSI) curves from which weighted usable areas (WUA) of habitat can be determined. Recently, two-dimensional (2D) models have also been used to develop stream habitat metrics and analyze channel morphology [Ghanem et al., 1996; Crowder and Diplas, 2000a; 2000b; 2002; Waddle et al., 2000; Steffler and Blackburn, 2002].

More research is needed to gain a quantitative understanding of the linkages between fluvial morphology and aquatic habitat. Such an understanding will help in aquatic resource management, as well as promoting stream restoration activities based on sound fluvial morphologic principles. In this study, we explore these linkages by comparing stream geomorphic conditions, as assessed by VTANR [2004] protocols, to habitat conditions as predicted by a hydrodynamic modeling approach.

## 2. STUDY SITES

The six stream reaches in this study are a subset of a larger group of streams being analyzed by an interdisciplinary group of researchers in northwestern Vermont [Sullivan et al., 2004]. The stream reaches were selected according to geomorphic condition, drainage area, and plans for long-term study. The study reaches are all between 2nd to 3rd order (based on USGS 1:24,000 topographic maps), with drainage areas ranging from 22.7 to 36.8 km$^2$. The study reach lengths varied from 90 to 120 m as measured along the thalweg. The bankfull widths ranged from 6.6 to 14 m. A summary of stream reach characteristics is provided in Table 1.

**Table 1**. Summary of stream reach characteristics.

| | Drainage Area (km$^2$) | Bankfull Width (m) | Surveyed Length (m) | Bed D84 (mm) | Q50 (m$^3$/s) | Qbf (m$^3$/s) |
|---|---|---|---|---|---|---|
| Allen Brook | 27.86 | 6.6 | 120 | 28 | 0.376 | 6.37 |
| Beaver Brook | 30.49 | 14.5 | 100 | 260 | 0.412 | 7.01 |
| Fairfield River | 36.79 | 8.4 | 110 | 86 | 0.497 | 8.58 |
| Lee River | 34.83 | 10.8 | 90 | 86 | 0.471 | 8.08 |
| Mill Brook | 33.36 | 12.2 | 100 | 160 | 0.451 | 7.77 |
| Stone Bridge | 22.7 | 7.8 | 97 | 94 | 0.307 | 5.11 |

[Note: D84 = 84th percentile bed particle size; $Q_{50}$ = estimated median flows, probability of being exceeded 50% of time; $Q_{bf}$ = estimated bankfull flows]

## 3. METHODS

### 3.1 Rapid Geomorphic and Habitat Assessment

The Rapid Geomorphic Assessment (RGA) and the Rapid Habitat Assessment (RHA) are both part of the Vermont stream assessment protocol and are primarily qualitative in nature [VTANR, 2004]. RGA evaluates the stream condition according to four channel adjustment process: channel degradation (incision), channel aggradation, channel widening, and change in planform. Each of these four processes is scored (1 = poor, 20 = reference), summed, and divided by 80. Final scores of 0.00-0.34 are considered poor, 0.35-0.64 fair, 0.65-0.84 good, and 0.85-1.0 reference condition [VTANR, 2004].

Habitat assessments were conducted according the Vermont RHA protocols [VTANR, 2004], which are derived from the USEPA's Rapid Bioassessment Protocols [Plafkin et al., 1989; Barbour et al., 1999]. Specifically, we evaluated epifaunal substrate and available in-stream cover, degree of embeddedness, heterogeneous mixture of velocity and depth regimes, amount of sediment deposition, status of channel flow, degree of channel alteration, frequency of riffles, bank stability, vegetative protection and the width of the riparian vegetative zone. Each of these habitat parameters was assigned a value from 0 to 20. These values were aggregated according to the RHA to arrive at an overall habitat evaluation ranging from 0 to 200. As with the RGA, higher assessment scores indicate better aquatic habitat conditions.

### 3.2 Channel Characterization and Velocity Measurements

The bed particle-size distributions were determined using a modified Wolman [1954] pebble count method described by Potyondy et al. [1994] using a Wentworth gravelometer. At ten cross sections in each study reach, particle sizes were sampled at ten points incrementally across the stream. Pebble counts were completed for 2 riffle, 2 pool, and 2 run features, separately. Additionally, field observations were made as to the general type of bed surface to account for deposits or bed substrate differences in roughness values. These observations and particle-size distributions were intended as a guide in setting different bed roughness zones in the modeling calibration process.

A detailed topographic survey of each stream was completed using a total station to measure approximately every 0.5 to 1 m throughout the channel and up onto the floodplain (2000-3000 points per surveyed reach). The River2D model allows for indications of breaklines, or linear breaks in slope, in the topography, which can be very important to avoid problems in bed surface by Waddle et al. [2000]. Specific codes were developed and assigned in the total station's internal memory indicating the type of point taken, according to the stream feature they represented. This allowed easy assignment of the breaklines while inputting data to the model, as well as the ability to visually check the elevation model to assure that the points were accurate.

During baseflow conditions in late summer and fall of 2005, velocity and depth measurements were collected at the top and bottom of each study reach making sure to avoid areas of eddies or transverse flows using a Marsh-McBirney Velocimeter. These were then used to compute baseflow discharge ($Q_{meas}$) for use in calibrating the hydraulic model. In addition, randomly distributed velocity measures were collected approximately every 5 to 10 m along stream to compare to model results.

### 3.3 Hydraulic Modeling

The River2D model is a depth-averaged 2D hydrodynamic and fish habitat model which was designed for use in natural streams. River2D is a finite element model which uses a conservative Petrov-Galerkin upwinding formulation. Both subcritical and supercritical conditions can be accommodated and it has the capability to change the wet-dry perimeter. This is a transient model which can be set to obtain a steady state solution. A more detailed description can be found in the user manual [Steffler and Blackburn, 2002].As with most hydrodynamic finite element models, the model interpolates computational mesh properties from topographic data input and simulates depth and velocity at every node in that mesh. River2D was chosen due to its ability to predict fish habitat. Habitat Suitability Index (HSI) Curves containing known biological preference data for specific species are input and used to calculate WUA, a habitat assessment score based on stream hydraulics.

A computational mesh was created for each of the six streams. The lateral computational boundary was drawn close to the edge of water, while never contacting flow. A uniformly-spaced node formation was used with triangular elements close to a 45º angle. The approximate spacing of nodes was 0.2 m throughout the domain. Exceptions include area refinements to capture complex flow features where the mesh was made finer. This yielded a range of nodes per mesh between 32,445 for Mill Brook at bankfull flow ($Q_{bf}$) and 55,497 at Beaver Brook at median flow ($Q_{50}$).

The six reach models were calibrated at $Q_{meas}$ to ensure that the models represented the actual conditions within the streams. The inflow boundary condition, $Q_{in}$, as the field-measured discharge, $Q_{meas}$. The outflow boundary condition was the water surface elevation at the bottom of the reach, $WS_{out}$, which was measured at baseflow.

Only bed roughness values were slightly altered during calibration. Transverse eddy viscosity values were left at the default, as the velocities are insensitive to these values [Steffler and Blackburn, 2002]. All roughness values were left at reasonable values according to the bed substrate measurements. Steffler and Blackburn [2002] suggested using a bed roughness height larger than the largest bed substrate size in the stream. This value was set to the D84 substrate particle size for most of the streams. The exception was Allen Brook where the bed consisted of primarily sand and did require a roughness value equivalent of cobble sized bed. The models were considered calibrated when the $Q_{out}$ calculated by the model matched the $Q_{in}$ specified as the $Q_{meas}$, showing little error in discharge loss along the stream length. The distributed velocities measured in the field were compared with modeled values within the specific geomorphic feature measured.

The $Q_{bf}$ and $Q_{50}$ conditions were modeled using the calibrated models. Bankfull flow is a high flow considered to be the channel forming flow with a return interval of approximately 2 years. This flow was not measured in the field, but computed using regional curves created specifically for Vermont streams [VTANR, 2001]. The $Q_{50}$ is the median flow and was extrapolated from flow duration curves of East Orange Branch, a nearby gauged watershed of similar size (Drainage Area=23 km$^2$). The inflow boundary condition was set to the target flow value, while outflow boundary condition was determined by an iterative process. The $WS_{out}$ was set to various values bounding the bankfull elevation visible in the field and the WS value measured at $Q_{meas}$. The bed roughness was not changed from the values determined during calibration. The model was allowed to come to steady state and the specified $Q_{in}$ was compared to the model calculated $Q_{out}$. For all final $Q_{bf}$ and $Q_{50}$ models, the $Q_{out}$ was within 4 % of the $Q_{in}$ value at steady state, showing little water loss error along the length of the stream. The velocity vector lines were also checked to assure that they followed an expected path and did not exhibit erratic behavior.

### 3.4 Habitat Suitability Curves

The HSI curves used in this study were obtained from the U.S. Department of the Interior, Fish and Wildlife Service [Raleigh et al., 1986]. The brown trout species, *Salmo trutta*, at three life stages, adult, juvenile, and fry were considered using instream values of mean water column velocity, depth, and channel index. The channel index in this model is a categorical index of channel bed substrate size. Channel index was specified for each node in each stream model using a mapping approach, where areas of the stream can be specified and the value changed to reflect field conditions. An example HSI curve is shown in Figure 1.

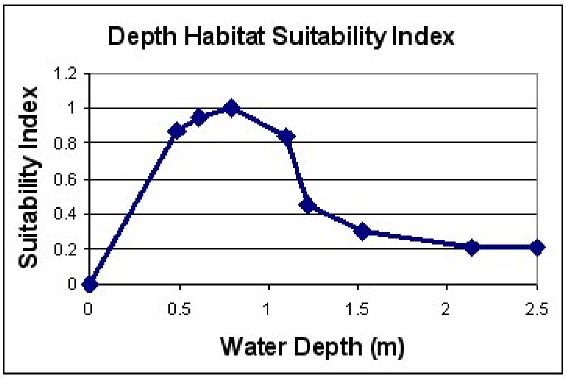


**Figure 1.** The HSI curve for adult brown trout according to water depth [Raleigh et al., 1986].

After obtaining steady state, HSI curves and channel index maps were loaded, and the habitat parameters for each node in the mesh were simulated. This calculation uses the modeled steady state values of velocity and depth, and the value of channel index from the input map, which is then used to locate corresponding HSI values for each parameter at each node. This yields the Velocity SI, Depth SI, and Channel Index SI, all scored between 0 and 1 for each node. These can be seen graphically for a section of Beaver Brook at baseflow in Figure 2. For each node these three values were multiplied together to form the Combined SI based on the Theissen polygon around the node to determine the WUA for each node. These individual nodal WUAs were then summed to determine the reach-scale WUA of habitat for brown trout in each stream.

## 4. RESULTS AND DISCUSSION

Model results show no correlation between WUA for any life stage of brown trout and discharge associated with $Q_{meas,}$ $Q_{50}$, or $Q_{bf}$. An optimal flow ranging between baseflow and bankfull was not found with only three discharges simulated. To find optimal discharge level for brown trout, more discharge levels must be included in analysis.

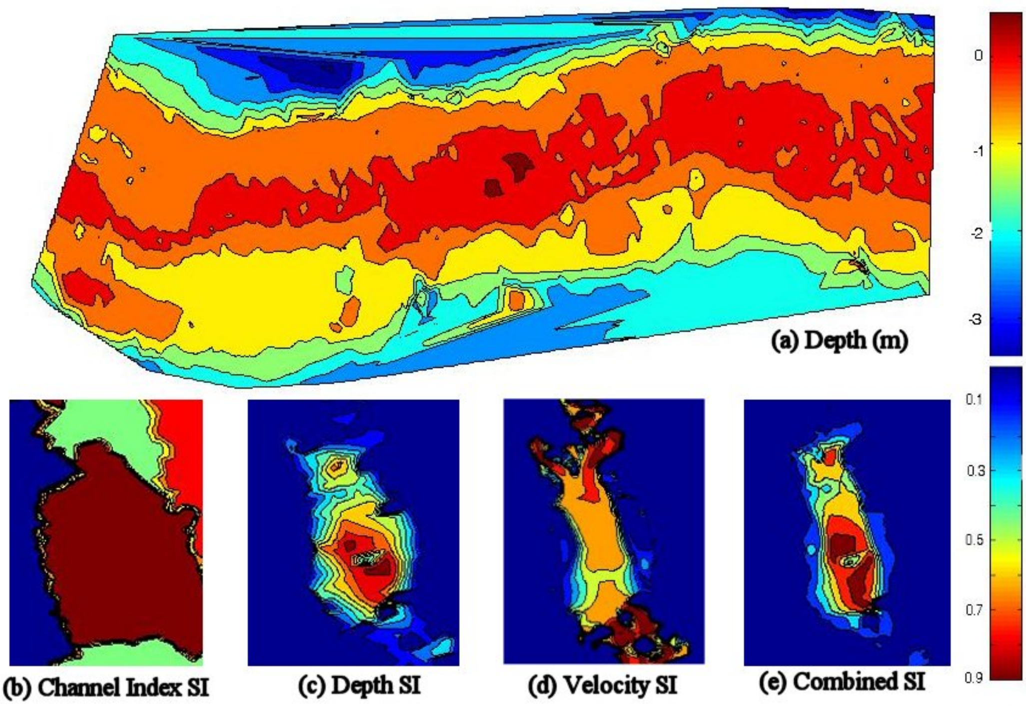


**Figure 2.** (a) Topography of Beaver Brook at $Q_{meas}$ after calibration is shown with water flowing left to right. Sub-panels show nodal values of suitability indices for (b) channel index, (c) depth, (d) velocity, as well as the (e) combined value for a subsection of the reach.

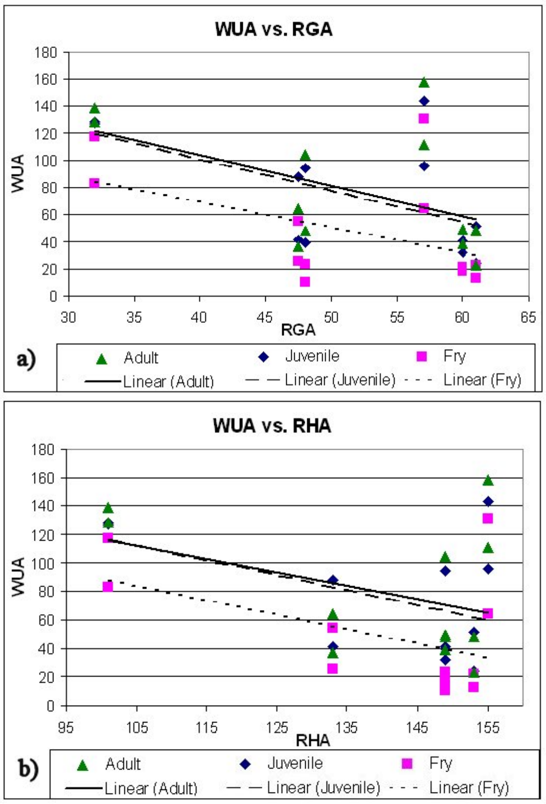


**Figure 3.** The reach-scale WUA calculated by the River2D model is shown in $m^2$ per 100 m of stream length for a) RGA and b) RHA score values.

There was a negative correlation between reach averaged values of WUA and RGA scores, with the WUA indicating higher available habitat for streams score low on the geomorphic scale (see Figure 3a). The hypothesis and assumption that better stream geomorphic condition translates into higher quality habitat was not shown in our analysis. In fact, streams with lower geomorphic conditions were found to have higher quality reach-scale habitat predicted by the WUA method.

A negative correlation was also found between reach-averaged WUA and RHA. Higher values of WUA correspond to lower RHA scores (see Figure 3b), which we did not anticipate. The RHA is a qualitative assessment of habitat characteristics and should indicate similar results to the hydraulically based habitat prediction of WUA. This indicates that at the reach scale, WUA and RHA do not indicate the same type of habitat availability.

The individual nodal values of WUA calculated by River2D are distributed in a patchy manner, as is obvious when estimated and mapped over the entire stream reach. For Beaver Brook, this distribution was examined further, calculating a WUA at increments of 10 m downstream. These incremental WUA values have high variance over the stream reach, ranging in values from 2.86 to 37.6 $m^2$ per 10 m length of stream (see Figure 4). This fluctuation of physical habitat conditions may be more important to classifying habitat than a single reach-averaged WUA score. The spatial distribution of habitat variables is not captured using either the reach-averaged WUA, or RGA and RHA assessment scores used to classify streams.

## 5. FUTURE WORK

Future investigations will include the analysis of additional stream reaches. In addition, a range of intermediate flows will be modeled to determine how habitat values vary across a range of discharge values. The frequency of discharge values will be determined and habitat availability will be determined as a function of time over a water year. More species will be considered in the calculation of River2D's WUA to determine if the results shown here are dependent upon the target species. Spatial analyses will be used to further evaluate the patchy nature WUA distributions. Finally, actual data on fish species in the streams will be compared to modeled habitat parameters.

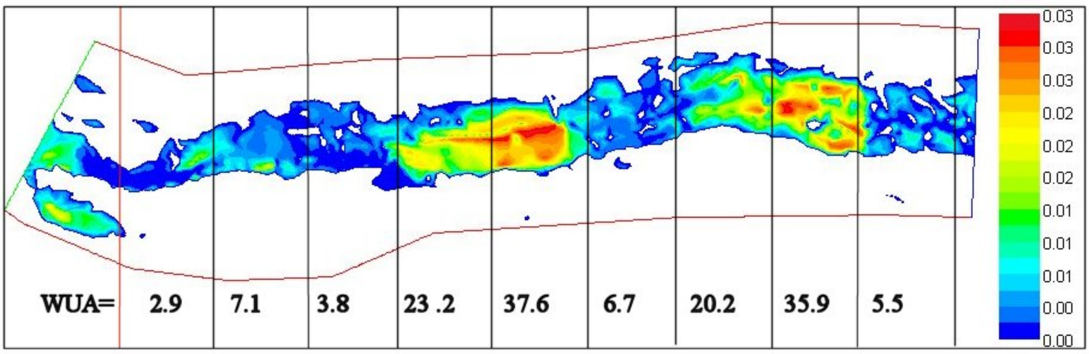


**Figure 4.** WUA is plotted in contour for Beaver Brook Adult Brown Trout at $Q_{50}$, with sectional WUA values shown for 10 m increments.

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